

# Water storage changes and balances in Africa observed by GRACE and hydrologic models

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## ABSTRACT

Continental water storage plays a major role in Earth's climate system. However, temporal and spatial variations of continental water are poorly known, particularly in Africa. Gravity Recovery and Climate Experiment (GRACE) satellite mission provides an opportunity to estimate terrestrial water storage (TWS) variations at both continental and river-basin scales. In this paper, seasonal and secular variations of TWS within Africa for the period from January 2003 to July 2013 are assessed using monthly GRACE coefficients from three processing centers (Centre for Space Research, the German Research Centre for Geosciences, and NASA's Jet Propulsion Laboratory). Monthly grids from Global Land Data Assimilation System (GLDAS)-1 and from the Tropical Rainfall Measuring Mission (TRMM)-3B43 models are also used in order to understand the reasons of increasing or decreasing water storage. Results from GRACE processing centers show similar TWS estimates at seasonal timescales with some differences concerning inter-annual trend variations. The largest annual signals of GRACE TWS are observed in Zambezi and Okavango River basins and in Volta River Basin. An increasing trend of 11.60 mm/a is found in Zambezi River Basin and of 9 mm/a in Volta River Basin. A phase shift is found between rainfall and GRACE TWS (GRACE TWS is preceded by rainfall) by 2–3 months in parts of south central Africa. Comparing GLDAS rainfall with TRMM model, it is found that GLDAS has a dry bias from TRMM model.

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## 1. Introduction

Satellite remote sensing provides more accurate monitoring of freshwater resources as it enables to move beyond the point-based observations provided by gauge networks. For

example, Smith [1] measured areas inundated by floodwaters using Landsat imagery.

Freshwater discharge from the continents is essential for understanding climatic and hydrologic processes in the Earth system via controls over water, energy and biogeochemical fluxes [2,3]. Gauge measurements helped to

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quantify flow in river channels. However, gauging networks are in decline globally. In addition, many river basins are marked by extensive wetlands and floodplains with ungauged flows [4]. Costs and logistics prohibit the installation of numerous gauges to characterize the flow within the total basin area. Yet, in many areas—including much of Africa and the Arctic—surface water flow is not measured [5].

Since 2002, the Gravity Recovery and Climate Experiment (GRACE) satellite mission has been used to monitor the Earth's gravity field over a large spatial scale. GRACE is currently measuring the Earth's mass redistributions with a spatial resolution of few hundred kilometers and monthly temporal resolution. GRACE provides maps of Earth's gravitational field from which one can infer trends in surface-mass anomalies [6–8]. Wahr et al. [9] reported that the primary cause of temporal changes in the Earth's gravity field is the redistribution of water mass within the Earth's relatively thin fluid envelope. GRACE measurements are already corrected for the major contribution of oceanic and atmospheric mass variations. Therefore, differences between two monthly solutions mainly reflect changes in terrestrial (surface plus ground) water storage between these two months [10]. For regions of 200,000 km<sup>2</sup> or more, GRACE can monitor changes in total water storage with an accuracy of 1.5 cm equivalent water thickness [11]. GRACE has the advantage to sense changes in water storage in all levels, including snow, surface water, groundwater, and soil moisture [12].

Few GRACE applications have been carried out to study water storage variations over Africa. Crowley et al. [13] estimated terrestrial water storage (TWS) within the Congo Basin in Africa for the period from April 2002 to May 2006 and found significant long-term trends yielding a total loss of approximately 280 km<sup>3</sup> of water over the period of study with a seasonal signal of  $30 \pm 6$  mm of equivalent water thickness. Kless et al. [14] compared monthly mean water storage variations inferred from GRACE in the upper Zambezi River sub-catchment (southern Africa) with the outputs of the (Lumped Elementary Watershed) LEW regional hydrological model. Moreover they quantified the influence of the atmosphere to GRACE monthly mean storage variations.

In addition, GRACE-derived estimates of land water storage have provided a good contribution to continental hydrology in global and regional scale [7,15,16]. Retrieval of hydrological signals in various large scale river basins have been successfully extracted from GRACE data [17–19].

Grippa et al. [20] estimated land water storage over West Africa using five years GRACE products and soil moisture estimated by regional land surface models (run within the framework of the AMMA Land Surface Intercomparison Project, ALMIP). Their results showed a good agreement between GRACE and model estimates. Their results pointed out the importance of correctly simulating slow water reservoirs as well as evapotranspiration during the dry season for accurate soil moisture modeling over West Africa. Xie et al. [21] used seven years of GRACE data and multi-site river discharge data to calibrate and evaluate a regional scale hydrologic model based on the Soil and Water

Assessment Tool (SWAT) model. Their study showed that there is less agreement between model- and GRACE-based TWS variations in arid and equatorial humid areas while SWAT was found to perform well in simulating total water storage variability in semi-arid and sub-humid regions. Other studies have been carried out with emphasis in the Niger River Basin Lake Chad [22].

In this paper, continental water storage variation is studied over Africa continent at seasonal and long term time scales using monthly GRACE spherical harmonics coefficients from three processing centers: Centre for Space Research (CSR) of the University of Texas at Austin, the German Research Centre for Geosciences (GFZ) and NASA's Jet Propulsion Laboratory (JPL). Monthly grids from 1° resolution Global Land Data Assimilation System (GLDAS)-1 and from 0.25° resolution TRMM-3B43 models are also used in order to estimate rainfall and evapotranspiration rates over Africa for the same period of study. Then, the GRACE TWS is investigated within the major river basins in Africa in comparison with the rainfall rates estimated from GLDAS-Noah model. Fig. 1 shows the study area with the major river basins and Table 1 shows the surface area of each basin [23,24].

## 2. Total water storage from GRACE

### 2.1. GRACE data processing

One of the main products of GRACE solutions is the level-2 time-variable gravity fields [25] which are monthly geopotential solutions released in terms of spherical harmonic coefficients. GRACE level-2 products are provided by a number of institutes, each employ different processing strategies and use different modeling for atmospheric and oceanic effects. The products used in this work are the latest Release-05 (RL05) L2

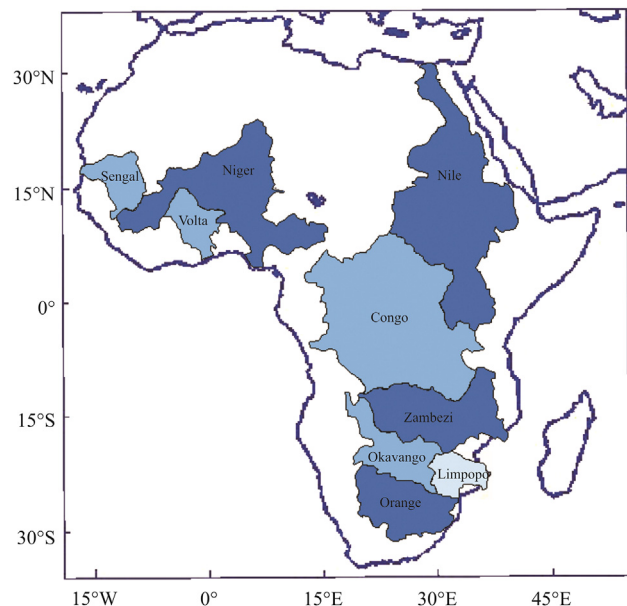


Fig. 1 – Major river basins in Africa.

**Table 1 – River basins' surface area and trend of GRACE TWS and rainfall rates over the major river basins in Africa (rivers arranged from north to south).**

River basin	Area (10 <sup>5</sup> km <sup>2</sup> )	Trend (mm/a)	
		GRACE	Rainfall
Nile	31.7	1.10	−0.36
Niger	22.7	5.90	0
Volta	4.07	9.00	1.12
Congo	38.2	1.30	2.18
Zambezi	13.9	11.60	1.04
Okavango	8.30	10.97	1.31

solutions provided by the three processing centers: the Centre for Space Research (CSR) of the University of Texas at Austin [26], the German Research Centre for Geosciences (GFZ) [27], and NASA's Jet Propulsion Laboratory (JPL) [28]. The set of data from GFZ and JPL were truncated to degree and order of 60 to be compatible with CSR data. The data for this study include 120 months covering the period from January 2003 to July 2013, with 7 months absent. Bettadpur et al. [29,30] proved that RL05 is more accurate than previously released GRACE products and is much less noisy than RL04 because of de-striping procedures applied to the data. Therefore, RL05 needs less spatial smoothing than earlier products.

In contrast to GFZ-RL04, the GFZ-RL05 estimates of  $C_{2,0}$  are much more plausible (i.e. much closer to SLR-based values). Therefore, GFZ recommends that users maintain the RL05 estimates of  $C_{2,0}$ , while the CSR and JPL still recommend that users replace  $C_{2,0}$  estimates from Satellite Laser Ranging (SLR) [31]. Additionally, the monthly degree 1 coefficients (geocenter) were used from Swenson et al. [32]. In order to derive spatial maps of TWS anomalies, first, GRACE observations are corrected for correlated errors present in short wavelength components (high frequency). This is done by post-processing GRACE monthly solutions applying a moving window filtering method according to Swenson and Wahr [33]. Decorrelation is done with a filter width  $w = 5$  for spherical harmonics orders above 7 [34]. After de-striping, the spherical harmonic coefficients are smoothed with a Gaussian filter of 300 km half width, using the formula represented by Chambers [35]. The choice of Gaussian filter width is a compromise in that it removes noise (the striping effects) but still allows studying sub-basin regions. Then, residual gravity field solutions were computed with respect to the temporal mean over the considered study period [17].

## 2.2. TWS variations

The time series of GRACE TWS is fitted by least squares estimations using five terms: mean, annual sine and cosine, and semi-annual sine and cosine, taking  $t = 0$  at January 1st for phase calculations. For missing months, monthly GRACE solutions of TWS can be linearly interpolated based on values corresponding both to the previous and following months [36].

Fig. 2 shows the annual amplitude and phase (with respect to January 1st) of TWS in Africa from GRACE CSR, GFZ, and JPL

solutions. The three solutions show similar estimates at seasonal timescales with insignificant differences. Equatorial regions show large seasonal variations with annual amplitude reaching 160 mm. The largest annual amplitudes detected by GRACE occur in the western Africa in Volta River Basin and parts of Niger River Basin as well as in parts of south central Africa in regions of Zambezi and Okavango River basins. Amplitudes over Sahara Desert (North Africa) give an idea of the noise level in each solution because most of these regions are arid desert with almost no water resources.

Fig. 3 shows the trend of TWS in Africa from GRACE CSR, GFZ, and JPL solutions as well as the root mean square error (RME) of the residuals (after fitting the time series using the mean, annual sine and cosine, and semi-annual sine and cosine). It is notable that trend signals are more affected by stripes than the seasonal estimates. Both GFZ and JPL solutions are more dominated by stripes than the CSR solution. Except for GFZ which shows lower values, CSR and JPL show an increasing trend of 20 mm/a in Zambezi River Basin in south central Africa and of 15 mm/a in Volta River Basin in western Africa. GFZ solution shows a negative trend of around −8 mm/a in some parts of Congo River Basin in central Africa. JPL solution shows the highest root mean square (RMS) residuals while CSR shows the lowest RMS residuals.

## 3. Total water storage from GLDAS

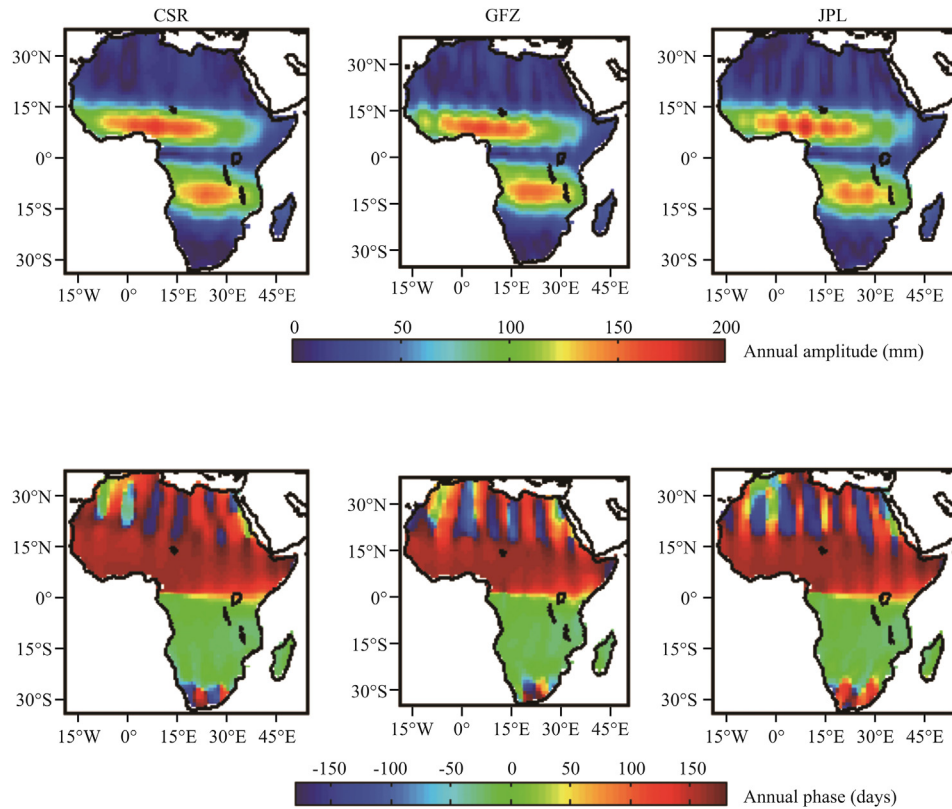
The Global Land Data Assimilation System (GLDAS) is a land surface simulation system which aims to ingest satellite- and ground-based observational data products, using advanced land surface modeling and data assimilation techniques, in order to generate optimal fields of land surface state (e.g., soil moisture, snow, and surface temperature) and flux (e.g., evapotranspiration, sensible heat flux) products [37]. Currently, GLDAS drives four land surface models; namely: the Community Land Model (CLM) [38], Mosaic [39], Noah [40], and the Variable Infiltration Capacity (VIC) [41].

In this study, data from the four land surface models of the GLDAS version1 (GLDAS-1) 1.0° resolution covering the period from January 2003 to July 2013 were used. Neglecting the small values in canopy water storage, the integrated GLDAS TWS is obtained by summing the layers:

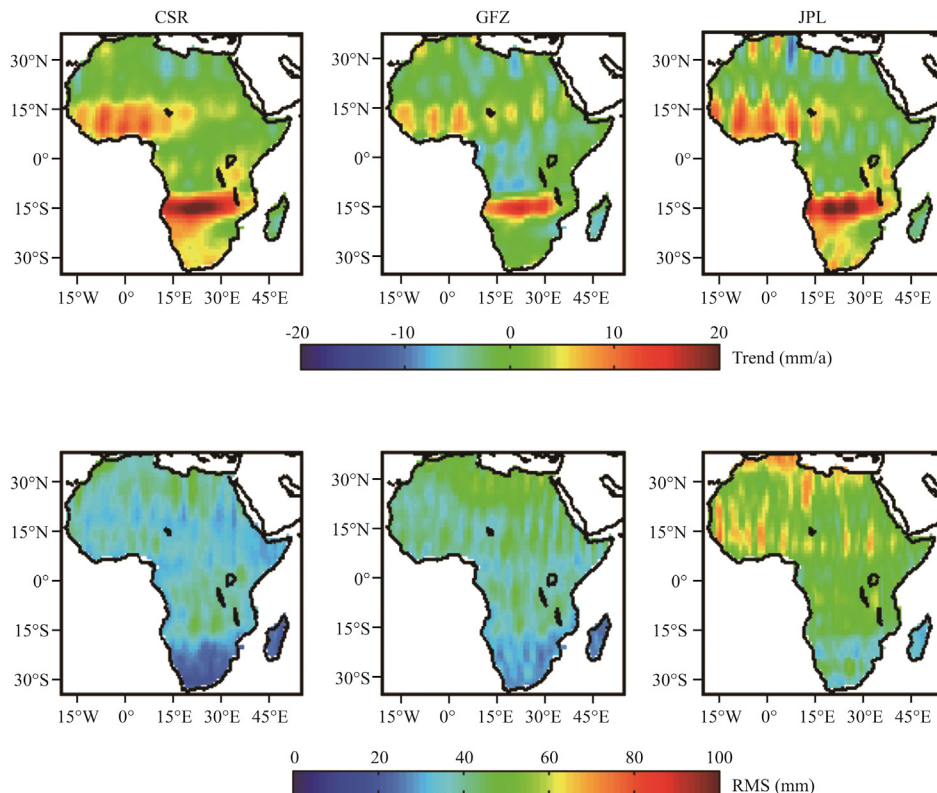
- % 86: SoilMoist1: Average layer 1 soil moisture: kg/m<sup>2</sup>
- % 86: SoilMoist2: Average layer 2 soil moisture: kg/m<sup>2</sup>
- % 86: SoilMoist3: Average layer 3 soil moisture: kg/m<sup>2</sup>
- % 86: SoilMoist4: Average layer 4 soil moisture: kg/m<sup>2</sup>

Except for Mosaic and VIC models which provide only three layers of soil moisture. The climate of the Africa is warm, so snow is uncommon. Therefore, GLDAS TWS estimated here is mainly reflecting the effect of soil moisture content. To be comparable with GRACE solutions, all models have been smoothed with the same Gaussian filter with 300-km half width.

Fig. 4 shows the annual amplitude and phase (with respect to January 1st) of the seasonal variations from the four GLDAS models. Except for CLM model which significantly has smaller amplitudes, GLDAS models show a good agreement with



**Fig. 2 – Annual amplitude (in mm of equivalent water thickness) (top panel) and phase (in days) (bottom panel) of the annual TWS variations in Africa from GRACE. Phase is calculated taking time  $t = 0$  at January 1st.**



**Fig. 3 – Trend (in mm/a) (top panel) and RMS (in mm of equivalent water thickness) (bottom panel) of TWS in Africa from GRACE.**



seasonal GRACE recovered TWS in terms of amplitudes, with the max signal appears in Zambezi River Basin in south central Africa. In terms of phase, there is a notable difference in the northern parts of Africa (Sahara Desert). In view of the lack of water resources in these parts of arid desert, this difference is considered to be of less importance in the comparison between seasonal variations of TWS from GRACE and GLDAS models.

Fig. 5 shows the trend of TWS in Africa from the four models of GLDAS as well as the RMS of the residuals (after fitting the time series using the mean, annual sine and cosine, and semi-annual sine and cosine). It is notable that the four models show different trend signals from GRACE TWS trend. GLDAS model is conceptually different from GRACE solutions as GLDAS does not account for groundwater variations [42]. Moreover, GLDAS cannot model changes caused by lakes' level variations. Mosaic, Noah, and VIC models show a positive trend in western Africa, but smaller than GRACE TWS trend. Only Mosaic model shows a negative trend in the west of Central Africa. In addition, Mosaic model (as well as VIC model) shows the highest RMS while CLM shows the lowest RMS. Note that CLM scale is smaller than the scale of the other models.

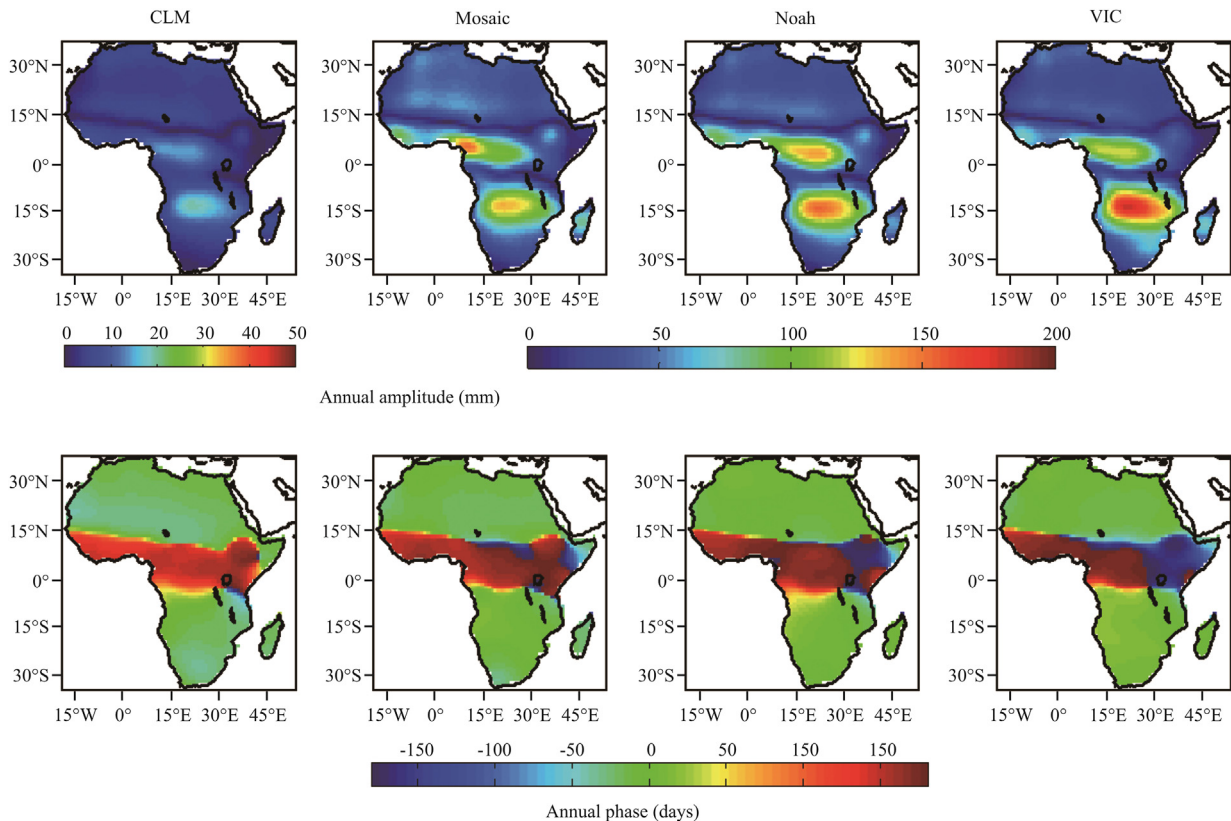
#### 4. Climate impact on TWS

In this section, the impact of rainfall and evapotranspiration to the TWS in Africa over the period from January 2003 to

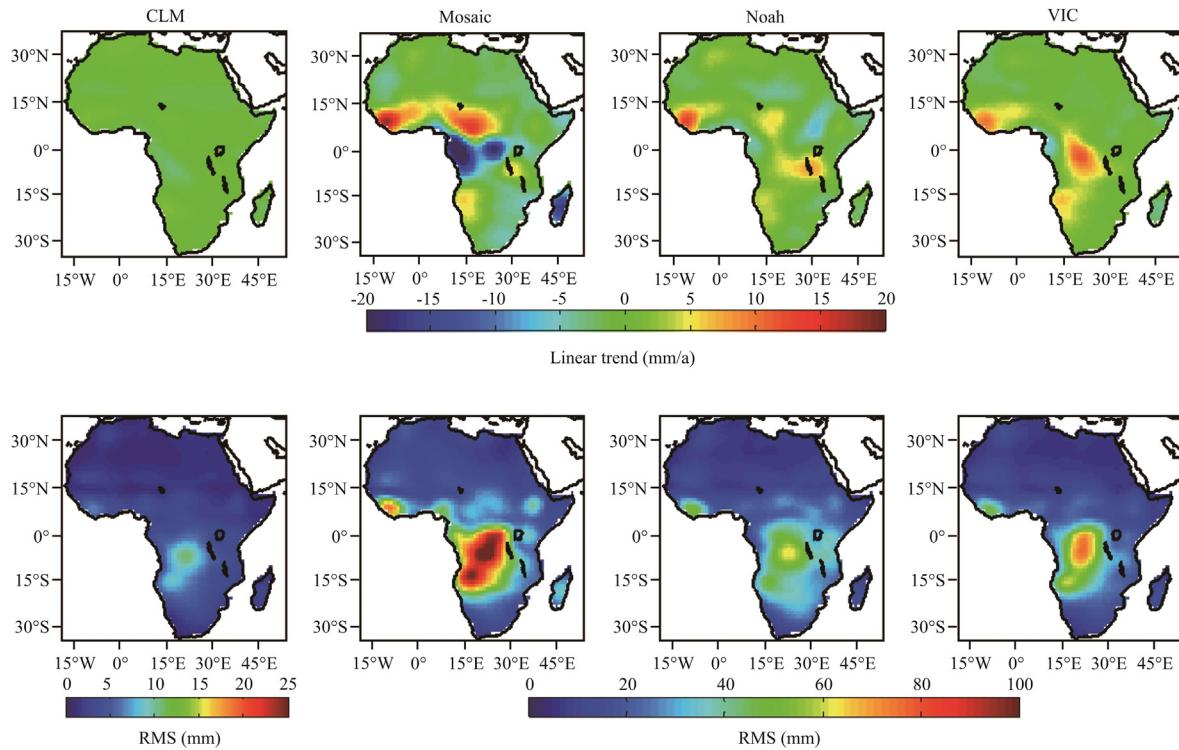
July 2013 is investigated. Monthly rainfall rates are estimated from GLDAS models as well as from the Tropical Rainfall Measuring Mission (TRMM). Monthly evapotranspiration (ET) rates are estimated from GLDAS models.

Launched in 1997, the main objective of TRMM is to measure rainfall rates of tropical and subtropical regions in the latitude range  $\pm 50^\circ$  [43]. There are a number of products based on the TRMM observations, whose use is dependent upon the subject of interest. In this study, the global monthly grids from TRMM-3B43 products available  $0.25^\circ$  by  $0.25^\circ$  spatial resolution are used. This rainfall product employs TRMM observations as well as data from a number of other satellites and ground-based rain gauge data [44].

Fig. 6 shows the annual amplitude and phase of the seasonal variations of rainfall rates as estimated from TRMM model as well as the trend, and RMS of the residuals (after fitting the time series using the mean, annual sine and cosine, and semi-annual sine and cosine). While, the annual amplitudes of the seasonal variations of rainfall rates as estimated from the four GLDAS models are shown in Fig. 7. Fig. 7 shows that the CLM, Mosaic, Noah and VIC estimated rainfall all have similar fluctuations among them. Both Figs. 6 and 7 show that GLDAS rainfall amplitudes show similar pattern as TRMM rainfall amplitude but with smaller amplitude values, which means that GLDAS has a negative bias from TRMM model in the study region. Both show that the largest amplitudes are found in Zambezi and Okavango River basins in south central Africa. Large amplitudes can also be found in Volta River Basin in western Africa.



**Fig. 4 – Amplitude (in mm of equivalent water thickness) (top panel) and phase (days) (bottom panel) of the annual TWS in Africa from GLDAS models. Phase is calculated taking time  $t = 0$  at January 1st.**



**Fig. 5 – Trend (in mm/a) (top panel) and RMS (in mm of equivalent water thickness) (bottom panel) of TWS variation from GLDAS models.**

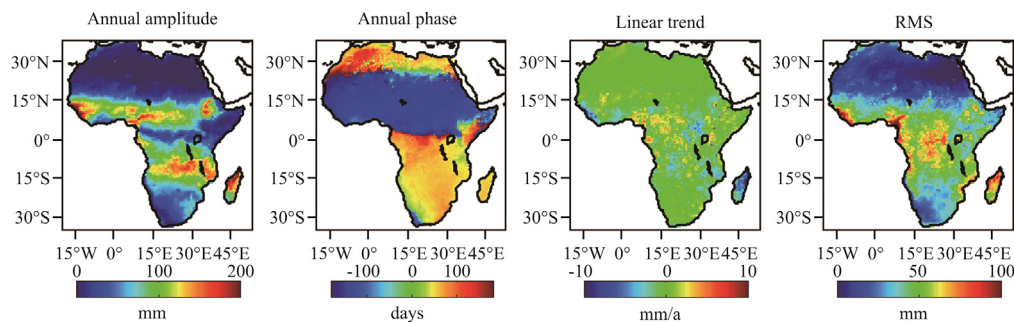
While Fig. 7 shows similarity between rainfall estimations from the four GLDAS models, Fig. 8 shows the annual phase, trend, and RMS of residuals from one model (Noah model). While the amplitudes show qualitative agreement with GRACE TWS amplitudes (Fig. 2), the annual phase shows a phase lag between GRACE TWS and rainfall (GRACE TWS is preceded by rainfall by about 1–2 months). Inter-annual trend from TRMM model does not show a significant increase or decrease of rainfall rates in Africa, while Fig. 8 shows an increasing trend of GLDAS rainfall rates in western and central Africa during the period of study. TRMM model shows higher RMS than GLDAS rainfall.

Fig. 9 shows the annual amplitudes and trend of the seasonal variations of evapotranspiration rates as estimated from the four GLDAS models. Like rainfall estimations, the four models have similar fluctuations in terms of amplitude with insignificant differences in case of Noah model. A

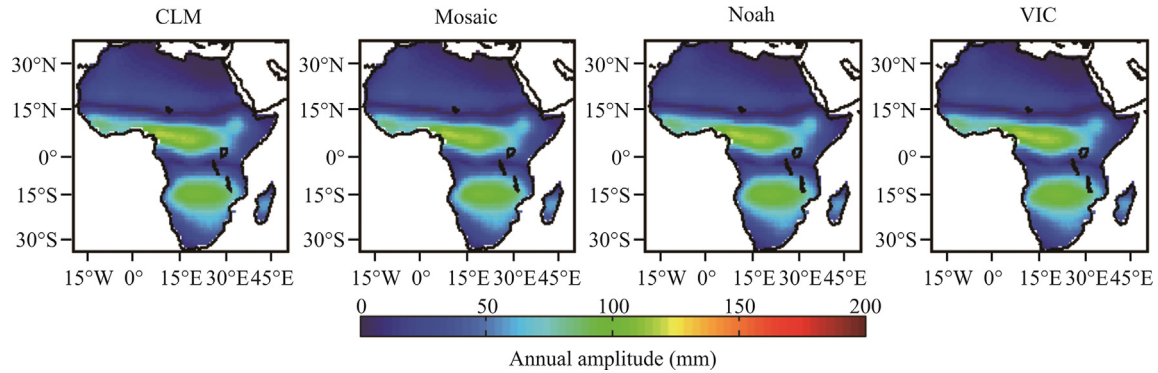
strong signal appears in central Africa and south central Africa with around 60 mm and 50 mm in amplitude respectively. Such areas (central Africa and south central Africa) have higher rainfall amplitudes of around 130 mm and 110 mm respectively (Figs. 6 and 7). Except for VIC model, all models show, to some extent, similar trends with a small positive trend in central Africa.

## 5. Water storage variations in major river basins of Africa

In this section, water storage variations for each individual river basin were studied from GRACE and hydrological model. Fig. 1 shows different major river basins in Africa and Table 1 shows the surface area of each basin. In the following, GRACE CSR solution will be used to recover TWS in each river basin,



**Fig. 6 – Annual amplitude and phase, inter-annual trend, and RMS of rainfall rates estimated from TRMM model. Phase is calculated taking time  $t = 0$  at January 1st.**



**Fig. 7 – Annual amplitudes (in mm of equivalent water thickness) of rainfall from GLDAS models.**

expressed in units of equivalent water thickness, as CSR solution gives the lowest RMS among the three GRACE solutions (Fig. 3). In addition, rainfall rate over each individual river basin is estimated from GLDAS-Noah model expressed in units of equivalent water thickness.

Fig. 10 shows the time series of GRACE TWS variations over the major river basins in Africa after applying a 6-months smoothing window. The dashed lines show the time series after removing the annual signal in order to emphasize low frequency signals. The largest seasonal signal appears in Zambezi, Okavango, and Volta River basins with a significant overall positive trend. Values of inter-annual trends over river basins are shown in Table 1. Congo and Zambezi River basins show a significant decrease in water storage between 2003 and 2006, probably related to severe drought reported in much of eastern Africa [45,46], and followed by a sudden increase during 2007.

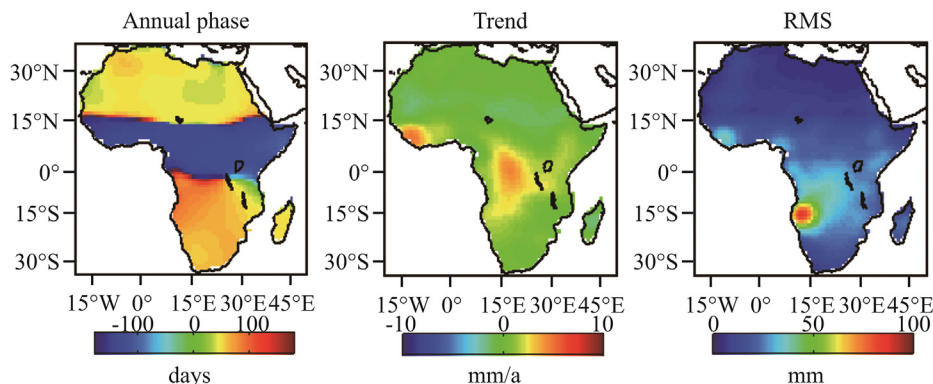
The time series of GLDAS-Noah rainfall rates over the major river basins in Africa are shown in Fig. 11 after applying the same 6-months smoothing window, while the dashed lines show the time series after removal of annual signal. Unlike GRACE TWS, max rainfall rate is observed within Congo River Basin with other positive trends shown over Zambezi, Okavango, and Volta River basins as shown in Table 1.

In order to investigate the impact of rainfall rates to TWS variations over each individual river basin, Fig. 12 shows the

seasonal cycle of GRACE-CSR TWS (solid line) in comparison with GLDAS-Noah rainfall rates (dashed line). For comparison, they are in a weak agreement in terms of amplitude and phase. Except for Congo River Basin, all figures show that rainfall precedes GRACE TWS by a phase shift (Table 2). For example, in case of annual time scale the phase lag is about 2.64 and 2.75 months for Zambezi and Okavango River basins, respectively.

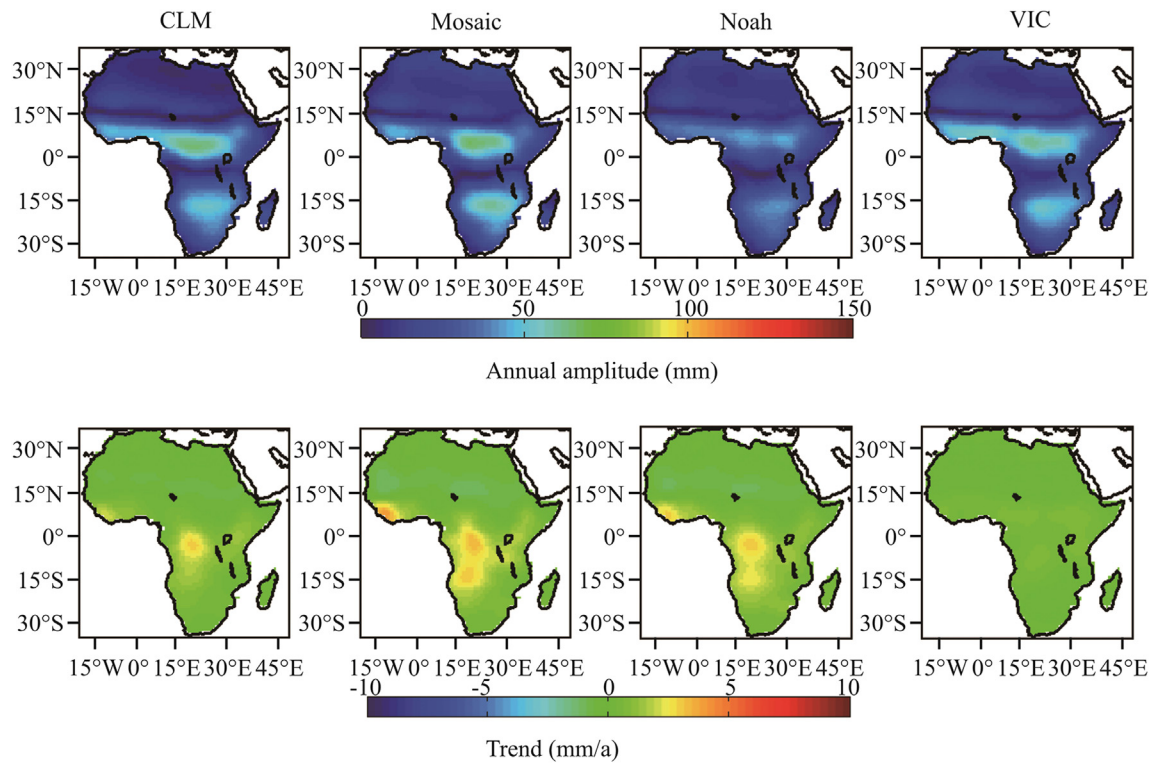
## 6. Summary and conclusion

Water storage changes over Africa continent are assessed in this study in order to detect mass changes and its reasons. To achieve this goal, GRACE monthly gravity field solutions from three processing centers (CSR, GFZ, and JPL) are used and compared with water storage changes from GLDAS hydrological model and with rainfall data from TRMM model. All the data are covering the period from January 2003 to July 2013. The results from the three GRACE solutions show insignificant differences in retrieval of continental TWS at seasonal time-scales, while CSR solution shows the lowest RMS of residuals. The largest annual amplitudes are found in Zambezi and Okavango River basins in south central Africa and in Volta River Basin in western Africa. Much smaller amplitude is observed in Sahara Desert in northern Africa which is an arid desert with almost no water resources. Long term trend of CSR



**Fig. 8 – Annual phase (in days), trend (in mm/a), and RMS (in mm of equivalent water thickness) of rainfall rates from GLDAS models.**

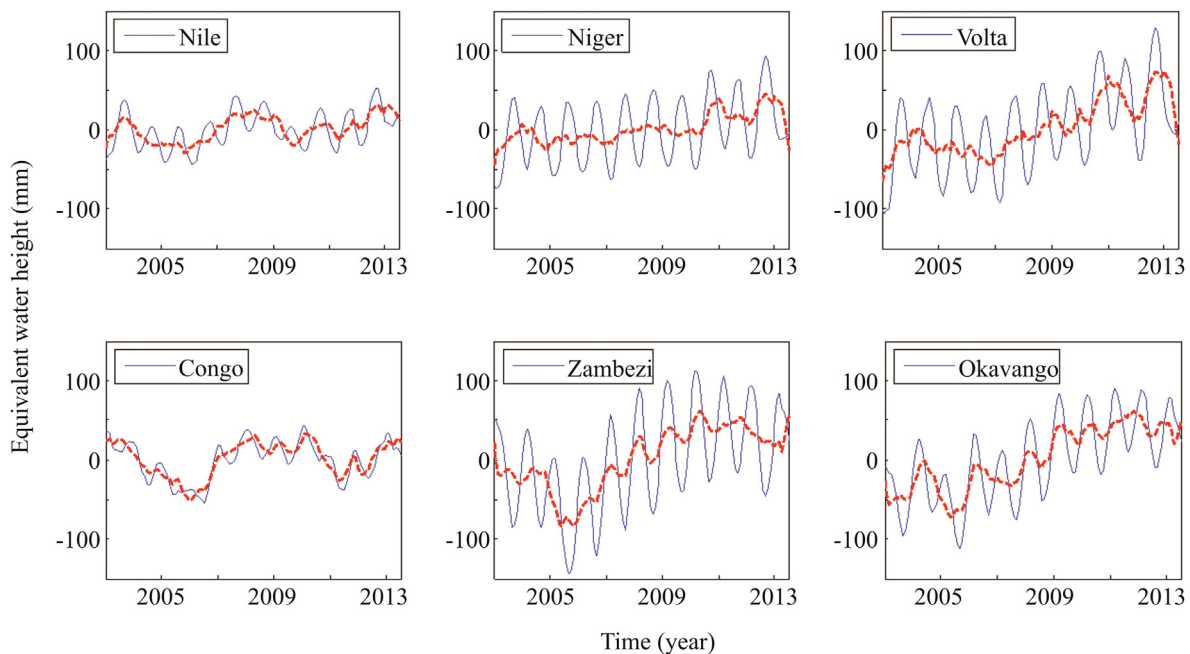




**Fig. 9 – Annual amplitudes (in mm of equivalent water thickness) (top panel) and trend (in mm/a) (bottom panel) of evapotranspiration rates estimated from GLDAS models.**

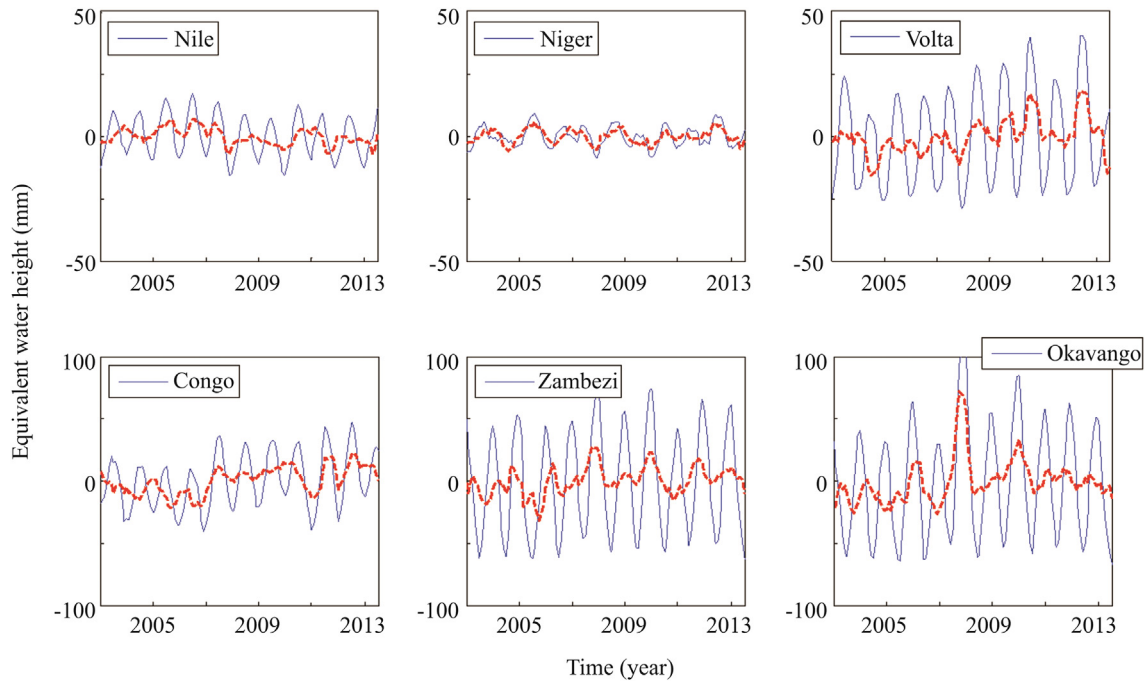
and JPL show an increasing trend of 11.60 mm/a in Zambezi River Basin in south central Africa and of 9 mm/a in Volta River Basin in western Africa. On the other hand, GFZ solution shows a negative trend of around  $-4$  mm/a in some parts of Congo River Basin in central Africa.

Four land surface models from GLDAS-1  $1.0^\circ$  resolution; CLM, Mosaic, Noah, and VIC are used to estimate water storage changes. CLM model shows significant smaller amplitudes than other models. GLDAS models (except for CLM model) show a good agreement with GRACE-derived TWS in



**Fig. 10 – Time series of GRACE-CSR TWS variation (solid line) and residuals after removing annual cycle (dashed line) of the major river basins in Africa expressed in equivalent water thickness (mm).**

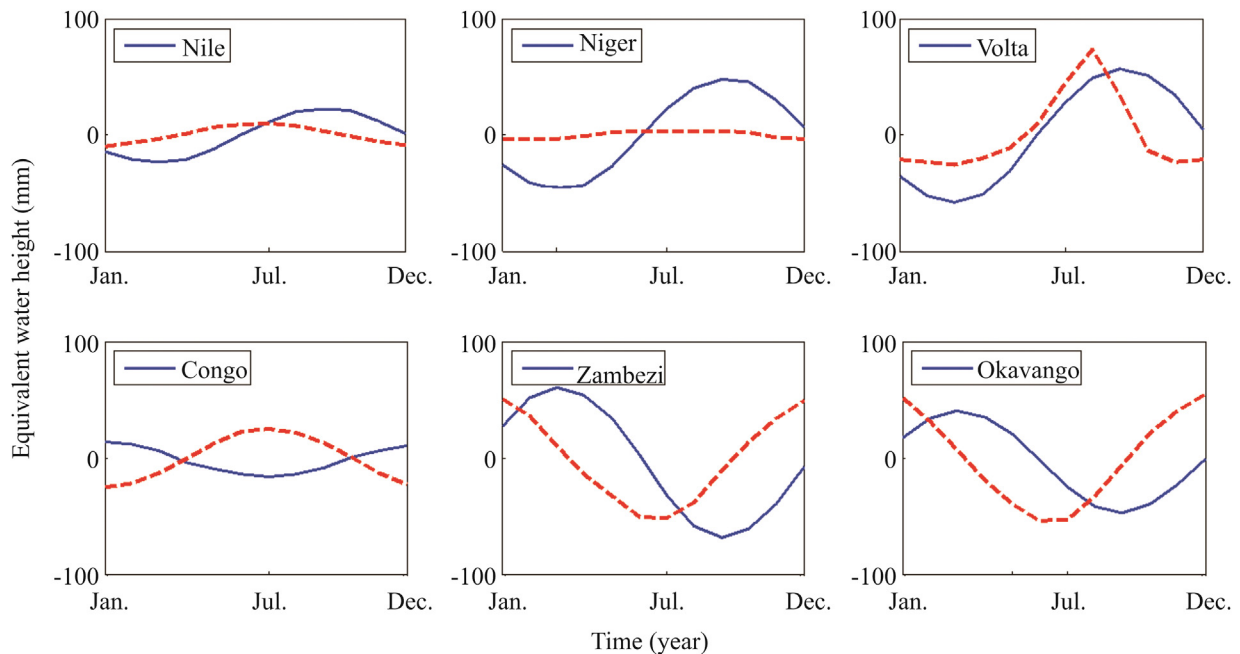




**Fig. 11 – Time series of GLDAS-Noah rainfall rates (solid line) and residuals after removing annual cycle (dashed line) over the major river basins in Africa expressed in equivalent water thickness (mm).**

terms of amplitude. Inter-annual trend of GLDAS shows variations from GRACE inter-annual trend of TWS because GLDAS is conceptually different from GRACE as GLDAS cannot model changes caused by groundwater and lakes' level variations.

Rainfall rates (as well as evapotranspiration (ET) rates) estimated from the four GLDAS models show similar fluctuations among them. The global monthly products at  $0.25^\circ$  resolution grids from TRMM-3B43 are used. The maximum amplitudes are found in Zambezi and Okavango River basins



**Fig. 12 – Seasonal cycle of GRACE TWS (solid line) and rainfall rates (dashed line) over the major river basins in Africa expressed in equivalent water thickness (mm).**

**Table 2 – Annual amplitudes and phases of GRACE TWS and rainfall rates over the major river basins in Africa (Rivers arranged from north to south).**

River basin	Annual amplitude (mm)		Annual phase (months)	
	GRACE	Rainfall	GRACE	Rainfall
Nile	44.51	16.37	5.10	−4.23
Niger	78.81	6.73	5.25	−4.96
Volta	121.17	39.53	5.20	−4.68
Congo	19.55	41.33	1.03	−4.45
Zambezi	118.84	84.87	−0.65	1.99
Okavango	70.06	89.20	−0.53	2.22

in south central Africa and Volta River Basin in western Africa, similar to the maximum GRACE TWS amplitudes. Therefore, it can be concluded that TWS in these parts is mainly dominated by rainfall as well as soil moisture content. However, a phase shift of 2–3 months is found between rainfall and GRACE TWS. GLDAS rainfall has a negative bias from TRMM model. Evapotranspiration estimated from GLDAS models show a good agreement with each other in terms of seasonal behavior while having some variations in terms of amplitude with the lowest ET estimates from CLM model.

## Acknowledgement

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